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EFFECT OF MELTING TANK DESIGN ON MELT HEAT EXCHANGE AND HYDRODYNAMICS IN A GLASS-MAKING FURNACE WITH HORESHOE-SHAPED FLAME DIRECTION

V. Ya. Dzyuzer¹ and V. S. Shvydkii¹

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Using a numerical model, the effect of the profile of the floor on hydrodynamics and heat exchange in the melting tank of a glass furnace was investigated. The different effect of the length and depth of the tank on formation of convection currents and heat exchange in different parts of the tank was established. Quantitative dependences between the linear dimensions of the deep part of the tank (beyond the sill) and some characteristics of the hydrodynamics and heat exchange in the tank were established.

To obtain specific output of glass furnaces above 2.0 – 2.5 tons/(m² · day), defined evolution of the traditional melting tank design has been proposed. Special attention has been focused on creating conditions that would ensure obtaining a homogeneous melt at the furnace outlet. The homogeneity of the glass melt is determined to a significant degree by the melting temperature and the residence time of new portions of the glass melt in the tank furnace. With all other conditions being equal, increasing specific output ineluctably decreases the time spent on the glass-melting process, which negatively affects the homogeneity of the glass melt obtained. The possibility of increasing the melting temperature (above 1580°C) is limited by the stability of the furnace design elements, where silica firebrick is used for the lining. For this reason, the modern approach to updating the melting tank design should be based on technical solutions that increase its blending power.

A simultaneous increase in the melting tank depth was provided for with an increase in the specific output in a certain stage of the development of glass furnaces. Objective grounds were created in this way for increasing the homogeneity of the melt. This tendency was realized by attaining higher furnace operating indexes. At the same time, the method of acting on the residence time of the glass melt in the tank and its homogeneity has many major drawbacks that limit its use.

The greater the depth (and volume) of the melting tank, the higher the heat consumption for maintaining the temperature potential of the circulating glass melt and compensating for heat losses to the environment. The quality of modern refractories and economic expedience limit the possibilities

of thermally insulating the side walls and floor of the tank. Heat losses through the tank lining can now be reduced to 900 – 1000 W/m². It is necessary to ensure sufficiently high thermal resistance of the lining, 1.2 – 1.5 K · m²/W. By keeping the temperature of the bottom layers of glass melt equal to 1250 – 1350°C, the possibilities of increasing the tank depth (as a function of the optical density of the glass) are restricted by limits of 1.8 – 2.5 m.

A solution of the problem of homogenizing glass melt in high-output furnaces is seen in using complex design solutions that effectively act on the hydrodynamics of the melt in conditions of judicious geometric construction of the melting tank. The overflow sill, bubbling, and additional electric heating are among the existing methods of affecting convection of the glass melt together with the depth of the bath and temperature field on its surface. The positive role of these methods consists of increasing the melt circulating factor in the basic contours and in this way acting on the melting time and homogeneity of the glass.

We conducted a detailed study of the “SDR – Sorg Deep Refiner” principle developed by the well-known German company, Sorg. The overall description of this principle given in information sheets allows considering it as a new method of acting on melt hydrodynamics. The deep part of the tank before the neck (Deep Refiner) is separated from the rest of the tank by an overflow sill. In this part of the bath, whose depth should be much greater than the depth of the melting zone, conditions are created which decrease the intensity of movement of return flow of the glass melt. Movement of the melt in the Deep Refiner zone is basically determined by its working flow. Descent of the glass melt into the neck and the much larger volume of this part of the tank in

¹ Ural State Technical University – UPI, Ekaterinburg, Russia.

comparison to the traditional execution increase the residence time of the melt in the bath and its homogeneity.

Using the numerical model of hydrodynamics in [1, 2], it is possible to study the effect of the geometric parameters of the Deep Refiner zone on formation of convection currents and the temperature field of the glass melt in the melting tank. A diagram of the tank is given in Fig. 1. For all versions of the calculation, the output and thermal load were considered constant: 300 tons/day and 16.867 MW, and the chemical composition of the glass was also considered constant (brand ZT-1). The temperature distribution on the surface of the glass melt corresponds to the total length of the flame tongue, equal to $L_v = 62.13$ m. In addition, the depth of the melt zone of the tank h_1 , height h_s , and width b_s of the sill and height h_{ne} of the neck are 1.3, 0.8, 0.4, and 0.3 m, respectively.

The boundary conditions for heat losses through the tank lining are reported in [3] and the other initial data are given in [4, 5].

The geometric parameters of the Deep Refiner are characterized by the vertical h_2 and horizontal Δx dimensions (see Fig. 1). The depth of the zone was set equal to $h_2 = 1.3, 1.5, 1.7, 1.9, 2.1, 2.3,$ and 2.5 m. The depth of the tank in front of the neck, $\Delta h = (h_{22} - h_1)$, varied from 0 to 1.2 m. The longitudinal coordinate of the position of the sill was set equal to $x_s = 9.2, 10.0, 11.2, 12.0,$ and 12.4 m. Five variants of the horizontal dimension of the Deep Refiner zone thus corresponded to all values of Δh : $\Delta x = 4.02, 3.22, 2.02, 1.22,$ and 0.82 m.

The results of numerical modeling were represented by two-dimensional fields of relative flow lines and glass melt temperatures. The flow lines were normalized to mass flow of the glass melt through the neck equal to 3.47 kg/sec. The method of changing the scale of the image was used for graphic representation of the picture of flow of the melt in different parts of the tank.

The homogeneity of the glass melt at the inlet into the neck was evaluated with the coefficient of thermal homogeneity calculated with the following algorithm.

Based on the nodal values of the melt temperatures $t_{w_{ne}}$ (we note that the hydrodynamic problem is solved by the method of finite differences in a square grid with a cell size of $\Delta z = 0.1$ m [1]), using the trapezoid method, we find its mean integral value:

$$\bar{t}_{w_{ne}} = \frac{\Delta z}{h_{ne}} [0.5t_{w_{ne}}(0) + t_{w_{ne}}(1) + t_{w_{ne}}(2) + 0.5t_{w_{ne}}(h_{ne})], \quad (1)$$

where $t_{w_{ne}}(0)$, $t_{w_{ne}}(1)$, $t_{w_{ne}}(2)$, and $t_{w_{ne}}(h_{ne})$ are the temperatures at the nodes of the grid with coordinates of $z = 0, 0.1, 0.2,$ and $h_{ne} = 0.3$ m.

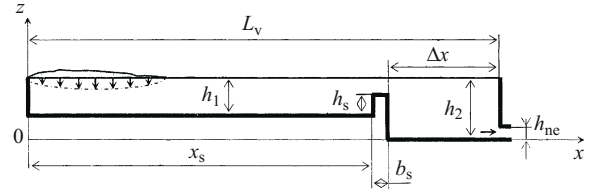


Fig. 1. Diagram of the longitudinal section of a glass-furnace melting tank with a horseshoe-shaped flame direction.

Using the quantity $\bar{t}_{w_{ne}}$ and the values of $t_{w_{ne}}$, we will calculate the standard deviation of the local (node) temperature σ (°C) from its average value:

$$\sigma = \sqrt{\frac{1}{4} \sum_{i=0}^3 [t_{w_{ne}}(i) - \bar{t}_{w_{ne}}]^2}, \quad (2)$$

where $t_{w_{ne}}(i)$ are the values of the node temperature at points with coordinates of $z = 0, 0.1, 0.2,$ and 0.3 m.

The results of the calculation with Eqs. (1) and (2) allow determining the coefficient of thermal homogeneity of the glass melt in the neck R (%):

$$R = 100 \left(1 - \frac{4\sigma}{\bar{t}_{w_{ne}}} \right).$$

Let us examine the effect of the depth of the tank Δh on the bath hydrodynamics at a constant value of $\Delta x = 4.02$ m corresponding to the longitudinal coordinate of the sill $x_s = 9.2$ m. We will compare the change in the distribution of the relative flow lines of the glass melt in the longitudinal section of the melting tank with the basic variant for which $\Delta h = 0$ ($h_1 = h_2 = 1.3$ m) [4]. At a constant tank depth, the melt flow picture (see Fig. 7 in [4]) is characterized by three circulation contours. In the melting part of the tank, two circulation contours with an interface at coordinate $x \approx 8.0 - 8.4$ m are observed. The left contour (here and below, the numbering of the contours is from left to right: from batch charging to neck) can be assigned to a developed bulk cycle contour. The second contour, limited on the right by the left wall of the sill, can be considered a local contour. The presence of an overflow sill not only impedes its horizontal development but also causes separation from the bottom of the bath. In the vertical plane, the size of the contour does not exceed 3/4 of the depth of the bath. One contour that occupies the entire volume of the tank beyond the sill is formed in the pure surface zone.

Transformation of the tank bottom profile ($\Delta h > 0$) primarily causes a change in the contour of the area of movement of the melt on which null boundary conditions, based on the flow function and boundary conditions based on heat transfer into the environment through the bottom and side

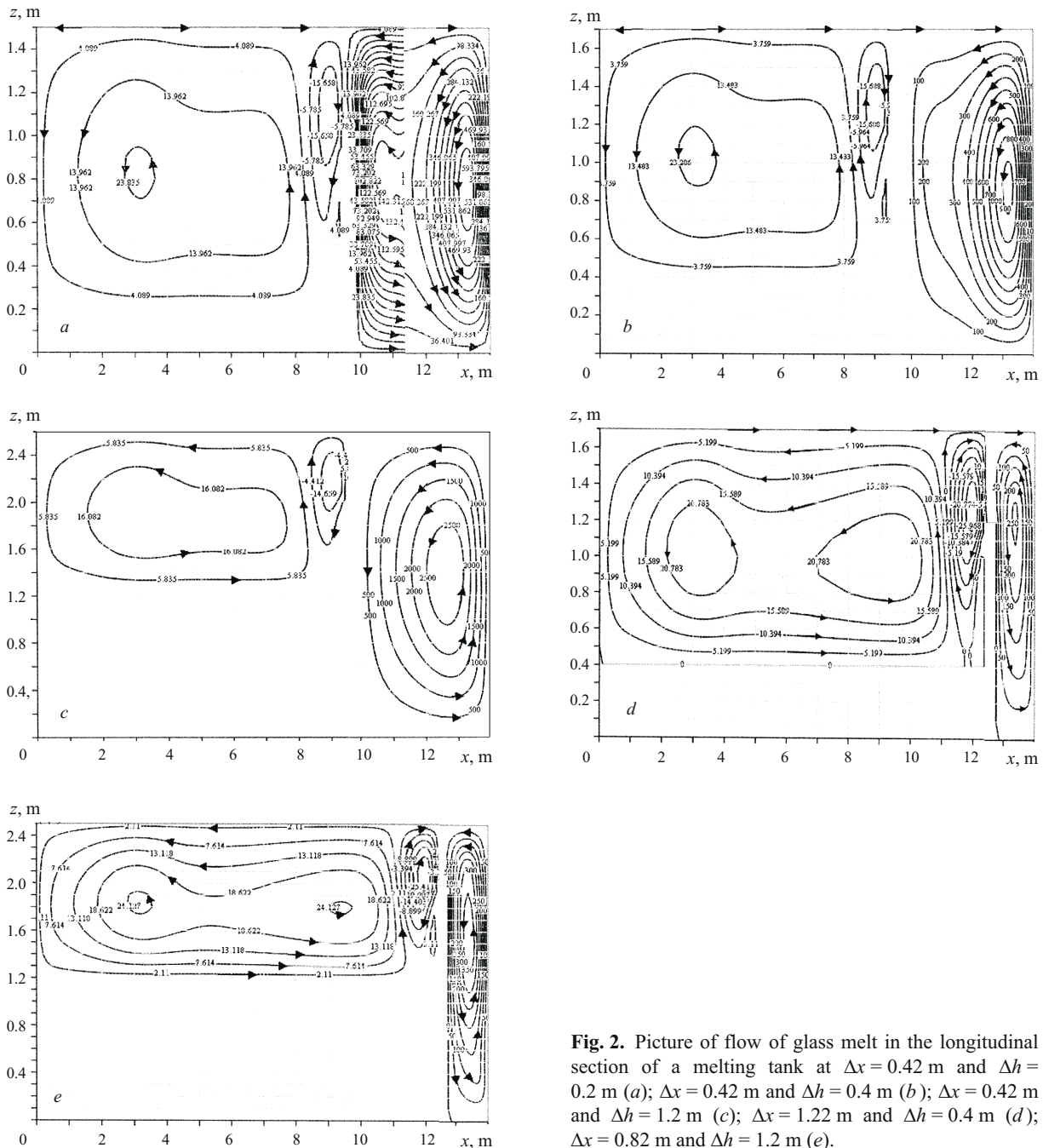


Fig. 2. Picture of flow of glass melt in the longitudinal section of a melting tank at $\Delta x = 0.42$ m and $\Delta h = 0.2$ m (a); $\Delta x = 0.42$ m and $\Delta h = 0.4$ m (b); $\Delta x = 0.42$ m and $\Delta h = 1.2$ m (c); $\Delta x = 1.22$ m and $\Delta h = 0.4$ m (d); $\Delta x = 0.82$ m and $\Delta h = 1.2$ m (e).

walls of the tank, are imposed. The picture of flow of the glass melt at a tank depth of $\Delta h = 2.0$ m is shown in Fig. 2a. Qualitatively, in comparison to the version with $\Delta h = 0$, the distribution of the relative flow lines up to the sill and the circulation factor of the glass melt in the first and second (local) contours remain almost unchanged. A relatively marked increase in the circulation factor K_c is observed with the same qualitative picture of flow of the melt after the sill. It increases from 451.1 ($\Delta h = 0$) to 655.7 ($\Delta h = 0.2$ m). In the given bath section ($\Delta x = 4.02$ m), the high-temperature surface layers of the glass melt circulate. For this reason, the in-

crease in the circulation factor not only compensates for the increasing heat losses through the side walls but also raises the mean integral temperature of the melt at the inlet into the neck from 1353.4 to 1357.7°C. The uniformity of the temperature distribution over the height of the bath simultaneously increases – the temperature drop in a significant part of the area beyond the sill does not exceed 15°C.

A further increase in the tank depth does not alter these characteristics. The circulation factor of the glass melt in the right part of the tank and its mean integral temperature in the neck increase with an increase in Δh . There are explicit nu-

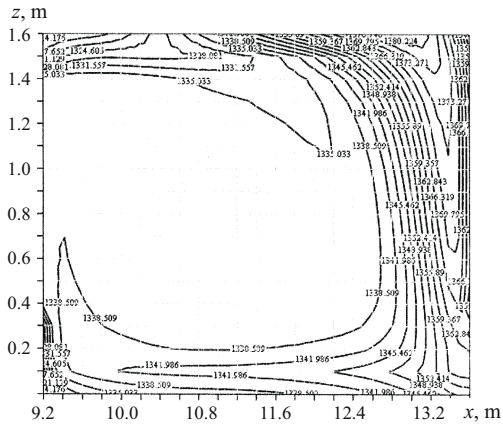


Fig. 3. Temperature field of glass melt after the sill at $\Delta x = 4.02$ m and $\Delta h = 0.4$ m.

merical dependences between these parameters (Δh , K_c , and $\bar{t}_{w_{ne}}$):

$$\bar{t}_{w_{ne}} = 1353.4454 + 23.2205\Delta h - 9.40625\Delta h^2;$$

$$K_c = 442.85079 + 895.60518\Delta h + 957.48125\Delta h^2;$$

$$t_{w_{ne}} = 1335.9294 + 0.054788K_c - 4.2297 \times 10^{-5}K_c^2 + 1.5681 \times 10^{-8}K_c^3 - 2.2010 \times 10^{-12}K_c^4.$$

The data in Fig. 2b and c, where the distribution of the normalized flow functions for $\Delta h = 0.4$ and 1.2 m are shown, give a graphic representation of the effect of the depth of the Deep Refiner zone on the hydrodynamics of the melt. They indicate that the qualitative picture of flow of the melt in the first (left) contour is preserved. The circulation parameters of this contour also remain almost unchanged. The relative constancy of the hydrodynamic situation also characterizes the second (local) circulation contour, caused by the resistance of the sill and flow around its edges. At the same time, both qualitative and quantitative changes can be seen in the third circulation contour (beyond the sill). This primarily concerns the structures of the contour. At $\Delta h = 0.4$ m, the small subcontour adjacent to the right wall of the sill and observed at $\Delta h = 0.2$ m disappears. With an increase in the tank depth, the center of the third (on the neck wall) contour is shifted toward the sill. The structure of the contour acquires the traits of more organized (steady-state) movement. There is a significant increase in the circulation factor. In the range of $\Delta h = 0.2 - 1.2$ m, it increases from 655.7 to 2888.0.

The important increase in the intensity of circulation of the glass melt in front of the neck should objectively cause an increase in the thermal homogeneity of the melt. The temperature distribution after the sill is shown in Fig. 3. In most of the Deep Refiner zone, the temperature of the melt varies from 1335 to 1338°C. On the whole, the temperature field in

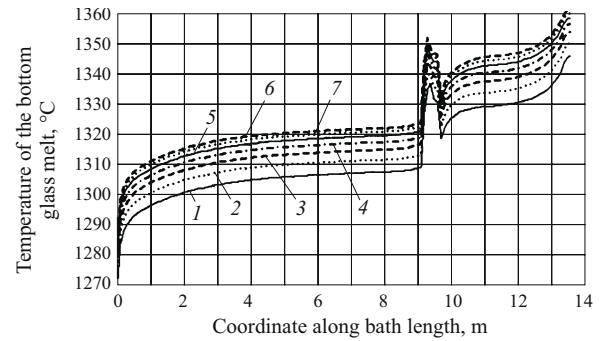


Fig. 4. Change in the temperature of the bottom glass melt: 1 - 7) $\Delta h = 0, 0.2, 0.4, 0.6, 0.8, 1.0$, and 1.2 m ($\Delta x = 4.02$ m).

this region is characterized by an average temperature equal to 1341.85°C, with a standard deviation of 12.01°C.

An increase in the intensity of circulation of the glass melt increases its average temperature in the neck and simultaneously improves the thermal homogeneity. The parameters of the temperature field of the melt in the neck at a different tank depth are reported in Table 1.

With a determination factor of $r^2 = 0.992442$, the dependence of the standard deviation on the tank depth can be written with the Harris model or quadratic parabola ($r^2 = 991857.0$):

$$\sigma = \frac{1}{0.21662538 + 0.010205773\Delta h^{1.2680881}};$$

$$\sigma = 4.6191667 - 0.16035714\Delta h - 0.048809524\Delta h^2.$$

The coefficient of thermal homogeneity is defined by the expression ($r^2 = 0.99505$):

$$R = 98.640357 + 0.030515873\Delta h + 0.078869048\Delta h^2 - 0.038194444\Delta h^3.$$

Let us examine the effect of the tank depth on the bottom layer of the glass melt. The data in Fig. 4 indicate that an increase in Δh will increase the temperature not only after the sill but also in the melting zone of the tank. The increase in the temperature at the bottom of the bath in the Deep Refiner zone is due to an increase in the circulation factor in the right (neck) contour. The increase in the left part of the tank in

TABLE 1

Δh , m	Temperature, °C, in grid nodes at z, m				$\bar{t}_{w_{ne}}$, °C	σ , °C	R, %
	0	0.1	0.2	0.3			
0	1345.3	1353.6	1355.1	1357.6	1353.38	4.615	98.640
0.2	1349.6	1357.8	1359.3	1362.1	1357.80	4.588	98.650
0.4	1353.3	1361.5	1363.0	1365.4	1361.28	4.548	98.664
0.6	1356.0	1364.2	1365.7	1368.0	1363.97	4.523	98.674
0.8	1358.0	1366.2	1367.6	1369.7	1365.87	4.436	98.701
1.0	1359.5	1367.7	1369.1	1371.1	1367.34	4.412	98.709
1.2	1360.7	1368.9	1370.2	1372.1	1368.36	4.361	98.725

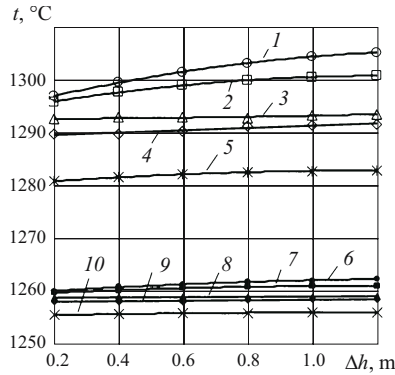


Fig. 5. Effect of depth Δh and horizontal dimension Δx of the tank on the glass melt temperature at two points near the bath surface: 1 – 5 ($t_{2,1,1}$) and 6 – 10 ($t_{2,1,2}$) [$\Delta x = 4.02, 3.22, 2.02, 1.22$, and 0.82 , respectively].

which the circulation factor of the glass melt is almost independent of Δh could only be due to replenishment of the left contour with high-temperature melt from the right part of the tank. If this hypothesis is correct, then the temperature of the melt near the surface of the bath in the melting zone of the tank should increase with an increase in the tank depth.

Figure 5 shows the change in the temperature at two points 100 and 200 mm away from the surface of the bath ($z = 1.2$ and 1.1 m, respectively) and positioned over the center of the front of entry of the primary melt into the bath ($x = 2.0$ m). We will designate the temperature at these points as $t_{2,1,2}$ and $t_{2,1,1}$. The data shown indicate that at $\Delta x = 4.02$ m, a change in the tank depth from 0.2 to 1.2 m will increase the temperature of the melt under the batch. For the point with coordinate $z = 1.1$ m (see Fig. 5, curve 1), it will increase from 1296.8 to 1305.3°C , and for $z = 1.2$ m (curve 6), from 1259.8 to 1262.2°C . This is also the cause of the increase in the temperature of the bottom layer of the glass melt.

For a given overflow sill position ($x_s = 9.2$ m) and horizontal tank dimension $\Delta x = 4.02$ m, an increase in the bath depth in the neck will thus cause an important increase in the circulation factor of the glass melt in this part of the tank. Blending the melt in the Deep Refiner zone not only increases the temperature of the glass melt in the neck but also its thermal homogeneity. The presence of reverse flow increases the temperature potential in the melting zone of the tank. On the whole, we note that for the indicated values of Δx and Δh , the SDR – Sorg Deep Refiner principle is only confirmed in the part of the increase in the melt homogeneity, characterized by the coefficient of thermal homogeneity of the glass at the inlet into the neck.

The 30 possible variants of the ratio of the linear dimensions of the deepened tank zone are given by the modeling boundary conditions. The wide range of variation of ratio $\Delta x/\Delta h = 0.683 - 20.100$ allows studying the effect of the geometric parameters of this zone on the hydrodynamics of the bath and heat exchange in the glass melt in more detail.

The analysis of the distribution of the relative flow lines shows that for the given values of $\Delta h = 0.2 - 1.2$ m, moving the sill toward the neck does not alter the qualitative picture of flow of the glass melt. In longitudinal section, the baths retain three circulation contours. The direction of rotation of the melt in these contours also remains unchanged. A change in the horizontal dimension of the contours corresponds to a change in parameters x_s and Δx . Only the appearance of two circulation subcontours, most distinctly manifested with a decrease in the horizontal dimension of the tank ($\Delta x < 2.02$ m) and relatively low values of its depth ($\Delta h < 0.6$ m) can be observed in the first contour (before the sill). Transformation of the linear dimensions of the circulation contours is shown in Fig. 2d and e.

The circulation factor of the glass melt in the first and second (local, left plane of the sill) contours varies within the limits of the error of calculation, i.e., it remains almost constant. At the same time, important changes in K_c are observed in the third contour, after the sill. The data in Fig. 6a suggest the complex character of the effect of the tank length and depth on the circulation factor in this contour. When $\Delta h = \text{const}$ persists, movement of the sill to the neck wall of the tank ($\Delta x \approx 4.02 - 3.60$) increases K_c . A further decrease in the horizontal dimension of the tank ($\Delta x \rightarrow 0.82$) is characterized by a multiple decrease in the circulation factor in comparison to the variant with $\Delta x = 4.02$ m. For $\Delta x = 0.82$ m, the value of K_c is comparable to the circulation factor in the first contour (before the sill). We can say that the suppression of convection of the melt at low values of the horizontal dimension of the Deep Refiner zone is due to an increase in the losses of kinetic energy of the viscous glass melt related to overcoming the friction forces on the side walls of the tank.

Similar changes in the circulation factor are observed with an increase in Δh and constant Δx . In the range of $\Delta h \approx 0.2 - 1.0$ m, increasing the tank depth will increase K_c . For the condition $\Delta h > 1$ m, the character of the change in the circulation factor of the glass melt is a function of the extent of the deep section of the tank.

As a result of processing the calculated data, we found that the dependence of the melt circulation factor after the sill on the tank dimensions with a determination factor of $r^2 = 0.9805$ is described by the equation:

$$K_c(\Delta x, \Delta h) = (-154.53166 + 344.21512\Delta x - 33.080434\Delta h - 69.39466\Delta x^2 - 2.2848364\Delta h^2 - 14.21057\Delta x\Delta h)/(1 - 0.24537293\Delta x - 0.77558235\Delta h + 0.014085662\Delta x^2 + 0.22217501\Delta h^2 + 0.079763245\Delta x\Delta h). \quad (3)$$

The analysis of Eq. (3) shows that function $K_c = f(\Delta x, \Delta h)$ has a maximum ($K_c = 3046.592$) located at the point with coordinates $\Delta x = 3.698441$ and $\Delta h = 1.014856$. From a physical point of view, the presence of a circulation factor maximum (in the given stage of the study) is not fully understood and requires additional analysis.

The character of the dependence of the hydrodynamics of the melt on the linear dimensions of the deep part of the tank is reflected in the characteristics of the change in the mean integral temperature of the glass melt in the neck (Fig. 6b). If condition $\Delta h = \text{const}$ is satisfied, then moving the sill nearer to the neck ($\Delta x \rightarrow 0$) will decrease the value of $\bar{t}_{w_{ne}}$, which is unconditionally due to a decrease in the circulation factor. The correlation of this temperature with the tank depth, which is greatly dependent on the concrete value of Δx , is more complicated. Note the relative constancy of the mean integral temperature of the glass melt in the neck at different values of Δh and the small horizontal dimension of the tank ($\Delta x < 1.0$ m).

It should be noted that the dependence of the mean integral temperature of the glass melt in the neck on the linear dimensions of the tank is subject to sufficiently clear mathematical description. With a determination factor close to unity ($r^2 = 0.9993$), function $\bar{t}_{w_{ne}} = f(\Delta x, \Delta h)$ is determined by the equation:

$$\begin{aligned} \bar{t}_{w_{ne}}(\Delta x, \Delta h) = & 1373.3706 - \frac{109.89217}{\Delta x} + 43.180082\Delta h + \\ & \frac{137.34551}{\Delta x^2} - 20.269493\Delta h^2 - 75.90712 \frac{\Delta h}{\Delta x} - \\ & \frac{58.969971}{\Delta x^3} + 4.9013275\Delta h^3 + \\ & 10.388139 \frac{\Delta h^2}{\Delta x} + 32.472434 \frac{\Delta h}{\Delta x^2}. \end{aligned} \quad (4)$$

The approximation of the two-dimensional function of the calculated values of the coefficient of thermal homogeneity of the glass melt in the neck is also sufficiently correct ($r^2 = 0.9822$):

$$\begin{aligned} R(\Delta x, \Delta h) = & 99.041216 - \frac{1.9730635}{\Delta x} - 0.42566838\Delta h + \\ & \frac{2.4131006}{\Delta x^2} + 0.31249318\Delta h^2 + 1.3946322 \frac{\Delta h}{\Delta x} - \\ & \frac{0.91774164}{\Delta x^3} - 0.077610781\Delta h^3 - \\ & 0.30469563 \frac{\Delta h^2}{\Delta x} - 0.53676133 \frac{\Delta h}{\Delta x^2}. \end{aligned} \quad (5)$$

An analysis of the data in Fig. 6c obtained with Eq. (5) will allow looking at some interesting applied characteristics of melt hydrodynamics in a new way. First, this concerns the traditional concept of the effect of convection of the glass melt on its homogeneity. The statement that melt homogeneity increases with an increase in the circulation factor is not totally correct when construction elements of the tank that alter its classic shape – a rectangular parallelepiped – act on formation of convection currents. These construction elements also include the presence of a deepened part of the tank beyond the sill. At certain values of Δx and Δh , a decrease in the melt circulation factor will not only not de-

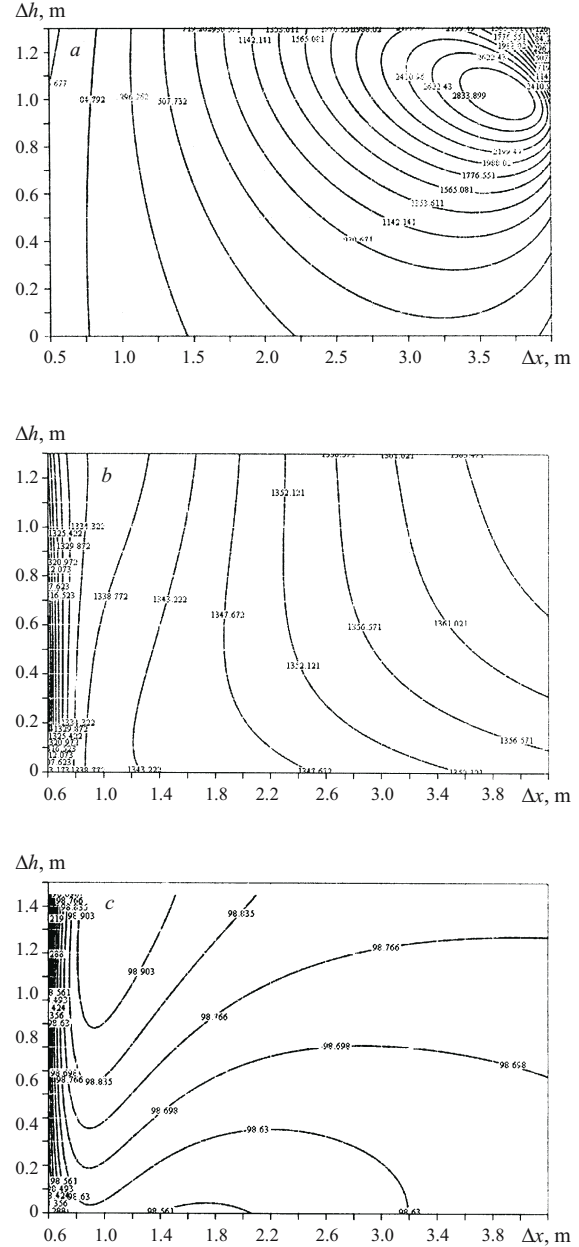


Fig. 6. Effect of tank size on the melt circulation factor after the sill (a), mean integral temperature of the melt in the neck (b), and change in the coefficient of thermal homogeneity of the melt in the neck (c).

crease, but will on the contrary increase the thermal homogeneity of the melt. Clearly the observed characteristic is due to the character of dependences (3) and (4) in Fig. 6a and b.

Use of the results of the study for practical construction of a melting tank implies determining how valid the use of parameters Δx and Δh or their ratio $\Delta x/\Delta h$ is for characterizing the structure of the bath part located after the overflow sill. At first glance, it is preferable to use the total height of the tank zone h_2 and ratio $\Delta x/h_2$ instead of the depth of the tank Δh . This hypothesis derives to some degree from the characteristic of the SDR – Sorg Deep Refiner principle. The

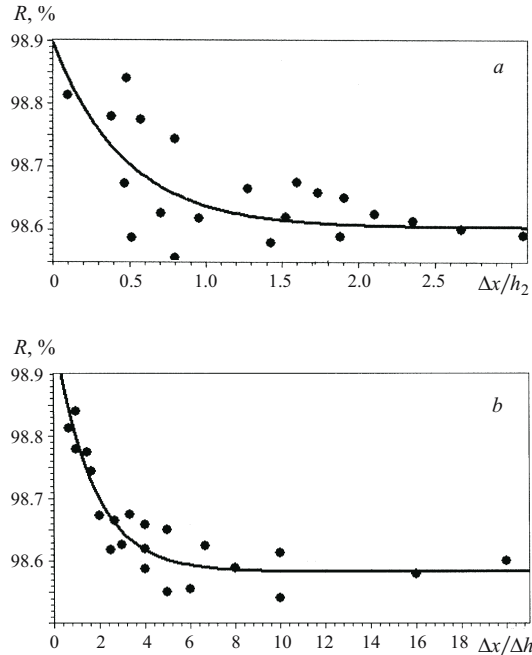


Fig. 7. Coefficient of thermal homogeneity of glass melt in the neck vs. ratio of the linear dimensions of the Deep Refiner zone (a) and tank (b).

coefficient of thermal homogeneity of the melt at the inlet into the neck can be selected as the defined (dependent) quantity since it reflects the integral manifestation of the hydrodynamics and heat-exchange characteristics observed in this part of the tank. The above can thus be reduced to the analysis of two functions: $R = f(\Delta x, h_2)$ and $R = f(\Delta x, \Delta h)$.

The graphic illustration of the equation $R = f(\Delta x, h_2)$ shown in Fig. 7a indicates that high scattering of defined quantity R is observed when ratio $\Delta x/h_2$ is used as an argument of the function. This a fortiori suggests the impossibility of correctly approximating the values in the graph. Actually, processing of the results by different mathematical methods showed that the logical model and rational function produce the greatest convergence. The first one, characterized by determination factor $r^2 = 0.67678838$, is represented by Eq. (6), given in the form of the approximating dependence in Fig. 7, and the second ($r^2 = 0.67187255$) is represented by Eq. (7):

$$R = \frac{98.654033}{1 - 0.0029627388 \exp\left(-2.1637351 \frac{\Delta x}{h_2}\right)}; \quad (6)$$

$$R = \frac{98.939604 + 124.6346 \frac{\Delta x}{h_2}}{1 + 1.2661437 \frac{\Delta x}{h_2} - 0.00068109372 \left(\frac{\Delta x}{h_2}\right)^2}. \quad (7)$$

The results of approximation of $R = f(\Delta x, h_2)$ with Eqs. (6) and (7) indicate that ratio $\Delta x/h_2$ is not representative

of the geometric characteristics of the deepened part of the melting tank. The data in Fig. 7b suggest that it is preferable to use the ratio of the length and depth of the tank ($\Delta x/\Delta h$) as an argument of function R . In these coordinates, the scattering of the analyzed values not only speaks of the character of the dependence $R = f(\Delta x, \Delta h)$ but also the possibility of its correct mathematical description. Approximation of the results of numerical modeling with the logistic function is characterized by a higher value of the correlation ratio $r^2 = 0.92130342$:

$$R = \frac{98.633579}{1 - 0.003911828 \exp\left(-0.60348396 \frac{\Delta x}{\Delta h}\right)}. \quad (8)$$

The graphic illustration of Eq. (8) in Fig. 7b shows the clear dependence of the coefficient of thermal homogeneity on the ratio of the geometric dimensions of the tank. We find that a real effect on coefficient R is observed at $\Delta x/\Delta h < 6 - 8$. At higher values of $\Delta x/\Delta h$, function (8) approaches "saturation." Selection of the argument $\Delta h = h_2 - h_1$ for characterizing the deepened zone makes it possible to also examine the depth of the tank melting zone (before the sill).

Let us consider the effect of the tank dimensions on heat exchange in the left part of the tank. It follows from the data in Fig. 5 that the temperature and selected control points ($t_{2,1,2}$ and $t_{2,1,1}$) is a function of both Δx and Δh . At $\Delta x = \text{const}$, increasing the tank depth causes an increase in the temperature of the glass melt at both points. For $\Delta h = \text{const}$, a decrease in Δx will decrease the temperature. The observed characteristics are satisfactorily correlated with the effect of Δx and Δh on the hydrodynamics and heat exchange in the deepened zone of the tank. They also indicate that the effect of the hydrodynamics of the right part of the tank on the left part (before the sill) persists for the investigated range of values of Δx and Δh .

The analysis of the two-dimensional functions [$t_{2,1,2} = f(\Delta x, \Delta h)$ and $t_{2,1,1} = f(\Delta x, \Delta h)$] describing the change in the temperature at the indicated points shows that relative independence of heat exchange in the left part of the tank only appears at low values of the horizontal dimension of the tank ($\Delta x < 1$ m). In this case, the change in the temperature is invariant to the value of Δh .

We can thus say that deepening the bottom of the bath behind the sill causes an increase in the melt circulation factor at the neck wall. This intensifies heat-exchange processes in both parts of the tank. In the melting zone, it is manifested by an increase in the temperature of the glass melt near the surface of the melt and consequently in the bottom layer. In the right part of the tank (after the sill), the temperature of the glass melt in the neck increases.

The effect of the tank depth on hydrodynamics and heat exchange is a function of the extent of the tank zone after the sill to a significant degree. The smaller the length of this

zone, the smaller the degree of manifestation of the positive effect of the tank depth on hydrodynamics and heat exchange in the bath. For $\Delta x < 1$ m, a significant decrease in circulation in the right contour almost total isolation from the hydrodynamics of the melting zone are observed.

Selecting a ratio of the tank length and depth implies a clear formulation of the requirements imposed on the hydrodynamics of the melt and organization of heat exchange in the melting tank. Suppressing melt circulation behind the sill and decreasing the temperature of the glass melt at the neck inlet are of practical interest for prolonging the lifetime of this construction element of the tank and the operating conditions of the working channel.

The results of the studies convincingly indicate that numerical modeling should precede the working design of the glass melting furnace. The formal use of such original solutions as the SDR – Sorg Deep Refiner principle in designing the melting tank can have negative results. It is clear that not only the real geometric parameters of the bath but also the most important properties of the glass (thermophysical and

optical), specific furnace output, etc., must be taken into consideration in defining the modeling boundary conditions.

REFERENCES

1. V. Ya. Dzyuzer and V. S. Shvydkii, "Numerical modeling of melt movement in glass melting furnaces," in: *Mechanics and Control Processes: Proceedings of the XXXIV Ural Seminar* [in Russian], Vol. 1, URO RAN Izd., Ekaterinburg (2004), pp. 125 – 136.
2. V. Ya. Dzyuzer and V. S. Shvydkii, "Mathematical model of the hydrodynamics of the glass furnace melting tank," *Steklo Keram.*, No. 1, 3 – 8 (2005).
3. V. Ya. Dzyuzer and V. S. Shvydkii, "Study of heat and mass exchange in the glass furnace melting tank," in: *Proceedings of the XXV Russian School and XXXV Ural Seminar on the 60th Anniversary of Victory: Part I: Science and Technology* [in Russian], Izd. RAN, Moscow (2005), pp. 181 – 196.
4. V. Ya. Dzyuzer and V. S. Shvydkii, "Effect of flame length on external heat exchange in a glass furnace with a horseshoe-shaped flame direction," *Steklo Keram.*, No. 7, 3 – 7 (2005).
5. V. Ya. Dzyuzer and V. S. Shvydkii, "Effect of flame length on the hydrodynamics of a glass furnace melting tank with a horseshoe-shaped flame direction," *Steklo Keram.*, No. 9, 5 – 11 (2005).